# Drell-Yan measurements in COMPASS

C. Quintans, LIP-Lisbon

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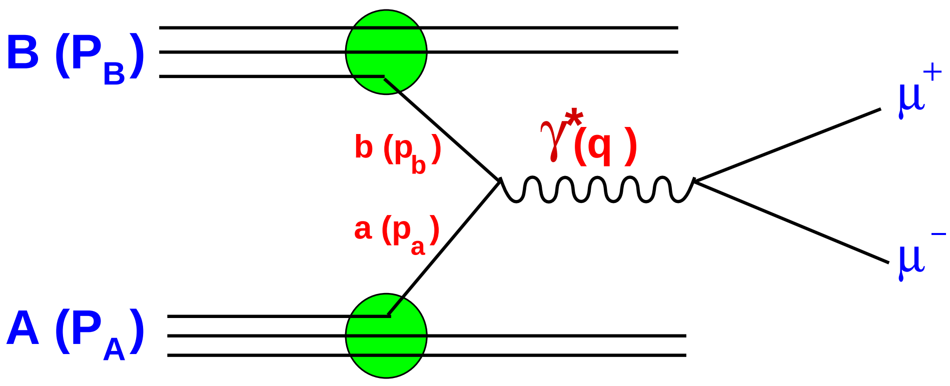
# Outline

- The Drell-Yan process
- Drell-Yan with transversely polarized target
- Drell-Yan at COMPASS: why and how
- COMPASS sensitivity to TMD PDFs
- Summary

# Drell-Yan process

Quark-antiquark annihilation, with dilepton production:




$$p_a = \sqrt{s}/2\, x_a(1,0,1)$$

$$p_b = \sqrt{s}/2\, x_b(1,0,-1)$$

$$q = p_a + p_b = (q_0, 0, q_L)$$

(massless quarks, collinear $\gamma^*$)

$$s = (P_A + P_B)^2 = \frac{\hat{s}}{x_a x_b} = \frac{\hat{s}}{\tau} \quad \Rightarrow \quad \tau = x_a x_b = \frac{\hat{s}}{s} = \frac{Q^2}{s} = \frac{M^2_{\mu\mu}}{s}$$

The hadronic cross-section is given by a convolution of parton distribution functions:

$$\frac{d\sigma}{dQ^2} = \sum_{q=u,d,s} \int dx_a \int dx_b \left( q(x_a)\bar{q}(x_b) + \bar{q}(x_a)q(x_b) \right) \hat{\sigma}_0\ \delta(Q^2 - \hat{s})$$

# Drell-Yan angular distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi(\lambda+3)}[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi]$$

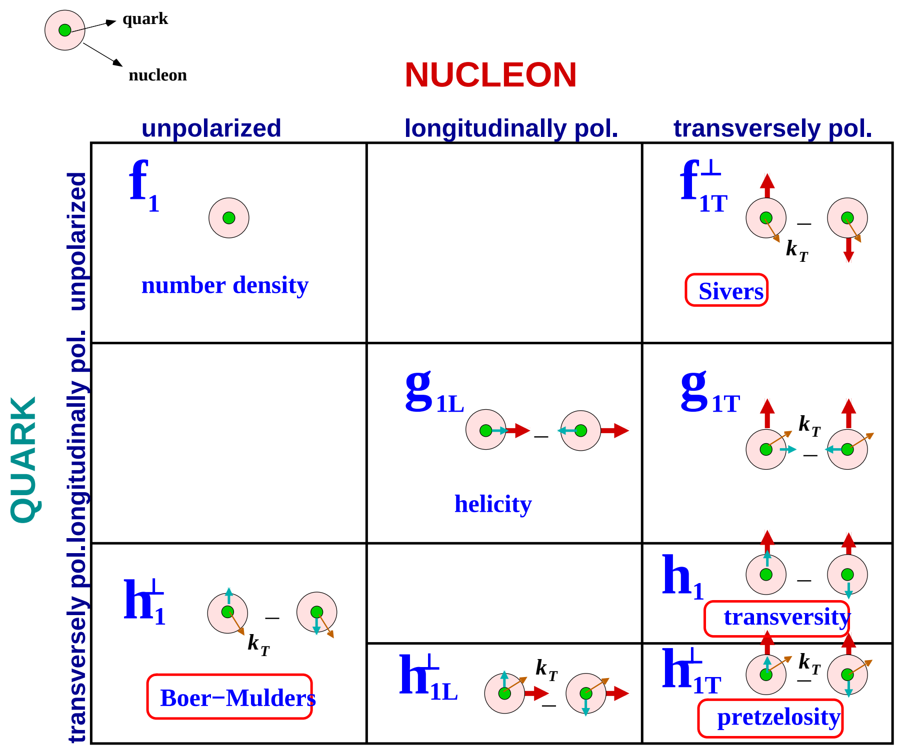
The collinearity hypothesis would imply $\lambda = 1$ and $\mu = \nu = 0$.

But experiments at CERN (NA10) and Fermilab (E615) measured important deviations from the collinearity hypothesis, with a modulation of $\cos 2\phi$ up to 30%!

This means we cannot neglect the intrinsic transverse momentum $k_T$ of quarks inside hadrons. Taking this into account, the $\gamma^*$ transverse momentum is $q_T = k_{Ta} + k_{Tb}$.

Nowadays the $\cos 2\phi$ modulation is believed to naturally arise from a product of 2 transverse momentum dependent (TMD) PDFs – the so-called Boer-Mulders PDFs of target and beam quarks interacting.

# Parton distribution functions




At leading order, 3 PDFs are needed to describe the structure of the nucleon in the collinear approximation.

But if one takes into account also the quarks $k_T$, 8 PDFs are needed.

This TMD PDFs approach is valid when $Q \gg q_T \gtrsim \Lambda_{QCD}$:
like in Drell-Yan at relatively small $q_T$, where we have $M_{\mu\mu} \gg p_T^{\mu\mu}$.

In the region $Q, q_T \gg \Lambda_{QCD}$, the collinear twist-3 approach should be used instead.

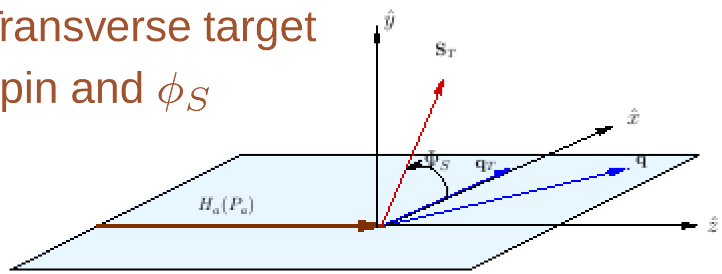
# Single polarized Drell-Yan

In the single polarized DY case (target transversely polarized), the general expression of the Drell-Yan cross-section (LO) is:

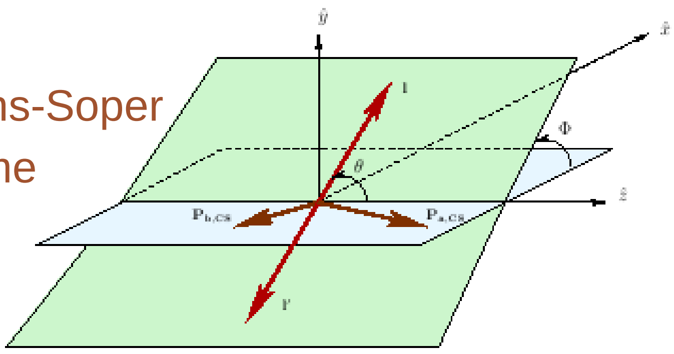
$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U\{(1 + D_{[\sin^2\theta]}A_U^{\cos 2\phi}\cos 2\phi)$$
$$+ |\vec{S}_T|[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)$$
$$+ A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S))]\}$$

- A: azimuthal asymmetries – $A_U^{\cos 2\phi}$, $A_T^{\sin\phi_S}$, $A_T^{\sin(2\phi+\phi_S)}$ and $A_T^{\sin(2\phi-\phi_S)}$
- D: depolarization factor
- S: target spin components
- $F = 4\sqrt{(P_a \cdot P_b)^2 - M_a^2 M_b^2}$
- $\hat{\sigma}_U$: part of the cross-section surviving integration over $\phi$ and $\phi_S$.

Transverse target spin and $\phi_S$



Collins-Soper frame



# *Azimuthal asymmetries*

Each asymmetry contains a convolution of 2 PDFs, one from target and another from beam quarks.

- $A_U^{\cos 2\phi}$: access to Boer-Mulders functions of incoming hadrons;
- $A_T^{\sin \phi_S}$: access to the Sivers function of target nucleon;
- $A_T^{\sin(2\phi+\phi_S)}$: access to Boer-Mulders function of beam hadron and to pretzelosity of target nucleon;
- $A_T^{\sin(2\phi-\phi_S)}$: access to Boer-Mulders function of beam hadron and to transversity of the target nucleon.

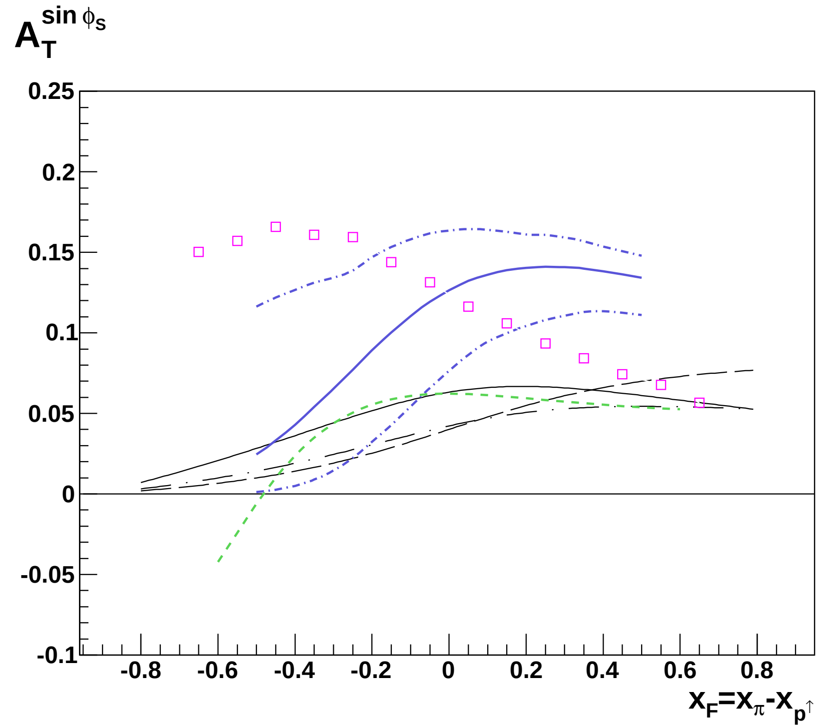
$\hookrightarrow$all to be measured experimentally

All these azimuthal asymmetries are expected to be sizable in the valence quarks region – where we measure.

# Theory predictions: $A_T^{\sin\phi_S}$

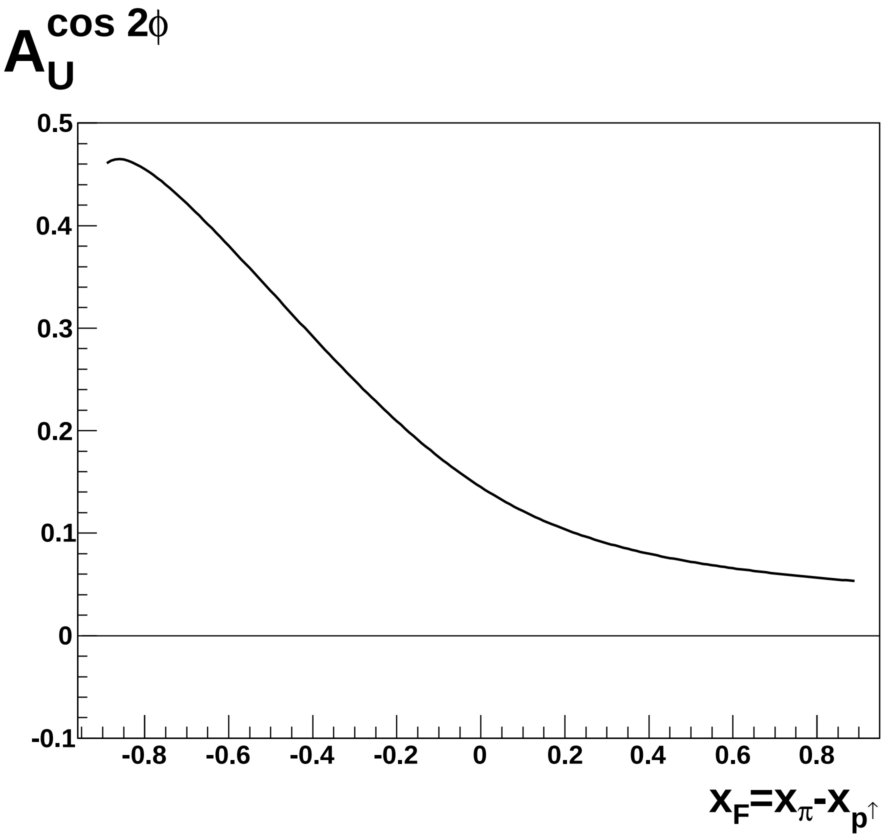
Sivers for DY 4.0 - 9.0 GeV/c$^2$,
from $\pi^-$ (190 GeV/c) $p^\uparrow$ collisions

– solid and dashed: Efremov et al,
PLB612(2005)233;
– dot-dashed: Collins et al,
PRD73(2006)014021;
– solid,dot-dashed: Anselmino et al,
PRD79(2009)054010;
– boxes: Bianconi et al, PRD73(2006)114002;
– short-dashed: Bacchetta et al,
PRD78(2008)074010.



# Theory predictions: $A_U^{\cos 2\phi}$

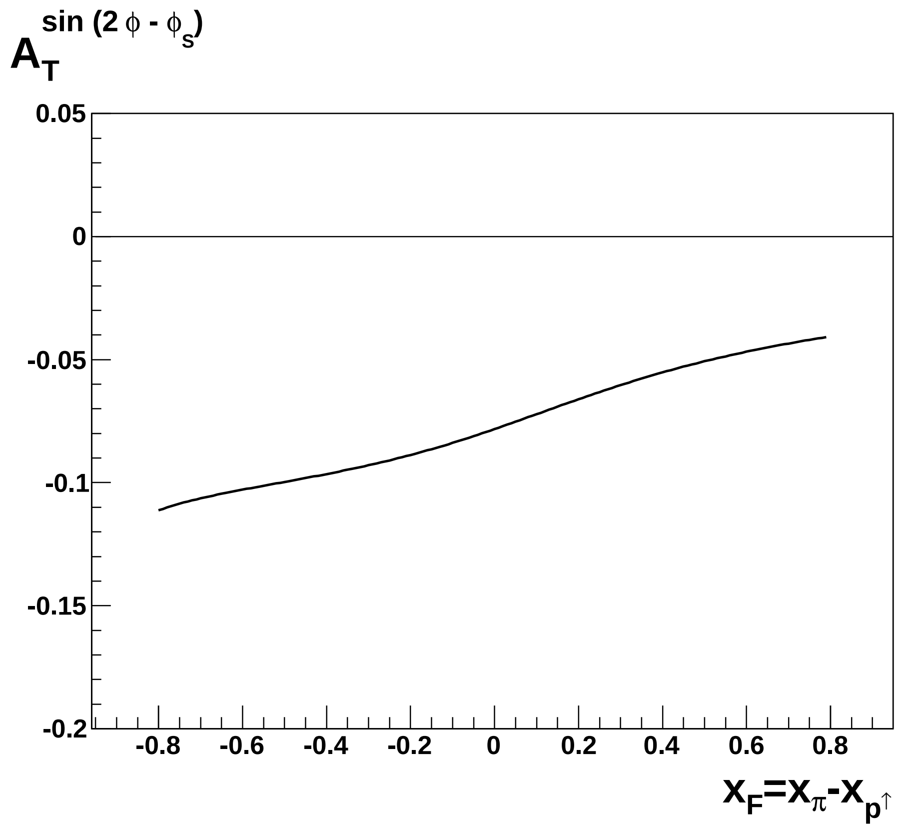
Boer-Mulders for DY 4.0 - 9.0 GeV/c$^2$,
from $\pi^-$ (190 GeV/c) $p^\uparrow$ collisions




B. Zhang et al, Phys. Rev. D77 (2008) 054011; with $\pi$ BM parametrization from D. Boer, Phys. Rev. D60 (1999) 014012 on NA10 data.

# Theory predictions: $A_T^{\sin(2\phi-\phi_S)}$

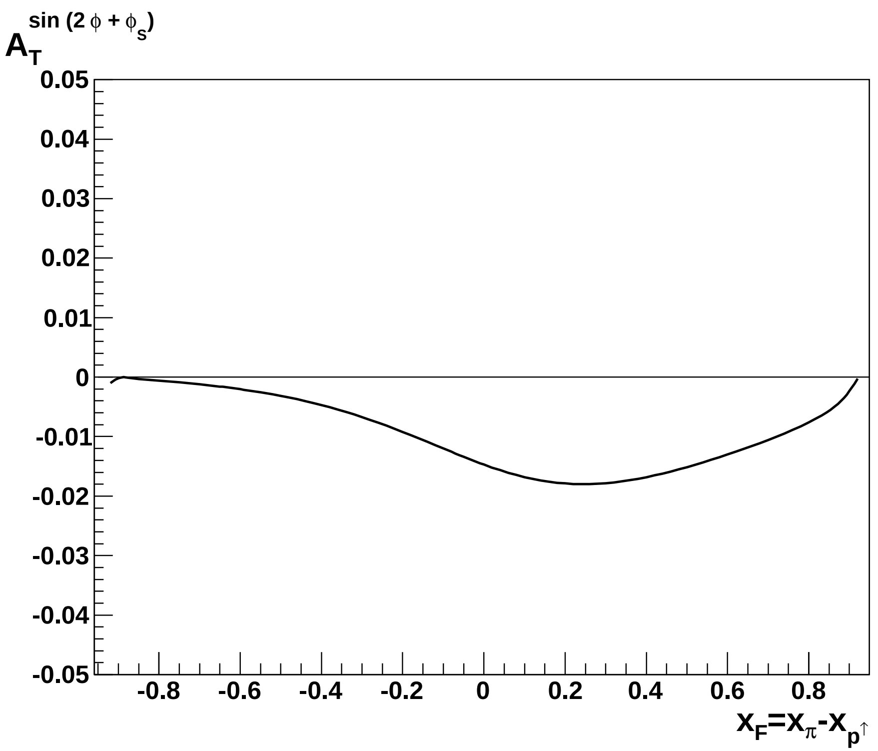
BM $\otimes$ transversity, for DY 4.0 - 9.0 GeV/c$^2$,
from $\pi^-$ (190 GeV/c) $p^\uparrow$ collisions




A.N. Sissakian, O.Yu. Shevchenko, A.P. Nagaitsev, O.N. Ivanov,
Phys.Part.Nucl.41:64-100,2010.

# *Theory predictions:* $A_T^{\sin(2\phi+\phi_S)}$

BM $\otimes$ pretzelosity, for DY 4.0 - 9.0 GeV/c$^2$,
from $\pi^-$ (190 GeV/c) $p^\uparrow$ collisions

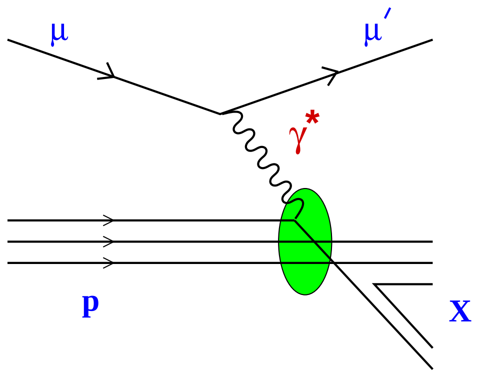



A. Efremov, B. Pasquini, P. Schweitzer, F. Yuan, in preparation.

Also recent prediction from Zhun Lu, Bo-Qiang Ma and and Jun She, with similar results.

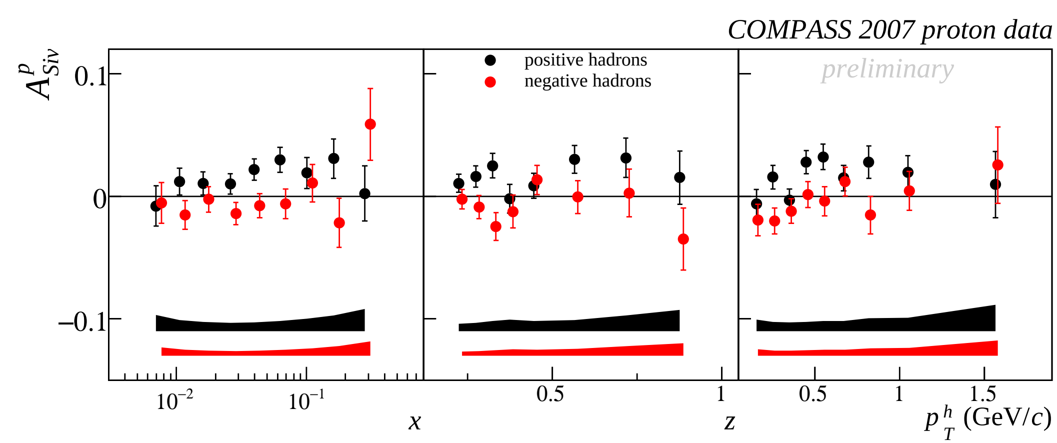
# TMD PDFs in SIDIS

Presently, our knowledge of PDFs in transversely polarized nucleons comes from SIDIS measurements (COMPASS and HERMES).




In semi-inclusive deep inelastic scattering the measured asymmetry results from the convolution of a nucleon PDF with a fragmentation function for the final state hadron.

The Sivers asymmetry was measured in COMPASS and HERMES.




The asymmetry is positive for $h^+$ on proton target (the effect in HERMES is larger by a factor 2 than in COMPASS).

# (Non-)Universality of TMD PDFs

Because the Sivers and Boer-Mulders PDFs are "time-reversal odd", they are expected to change sign when measured from SIDIS or from Drell-Yan:

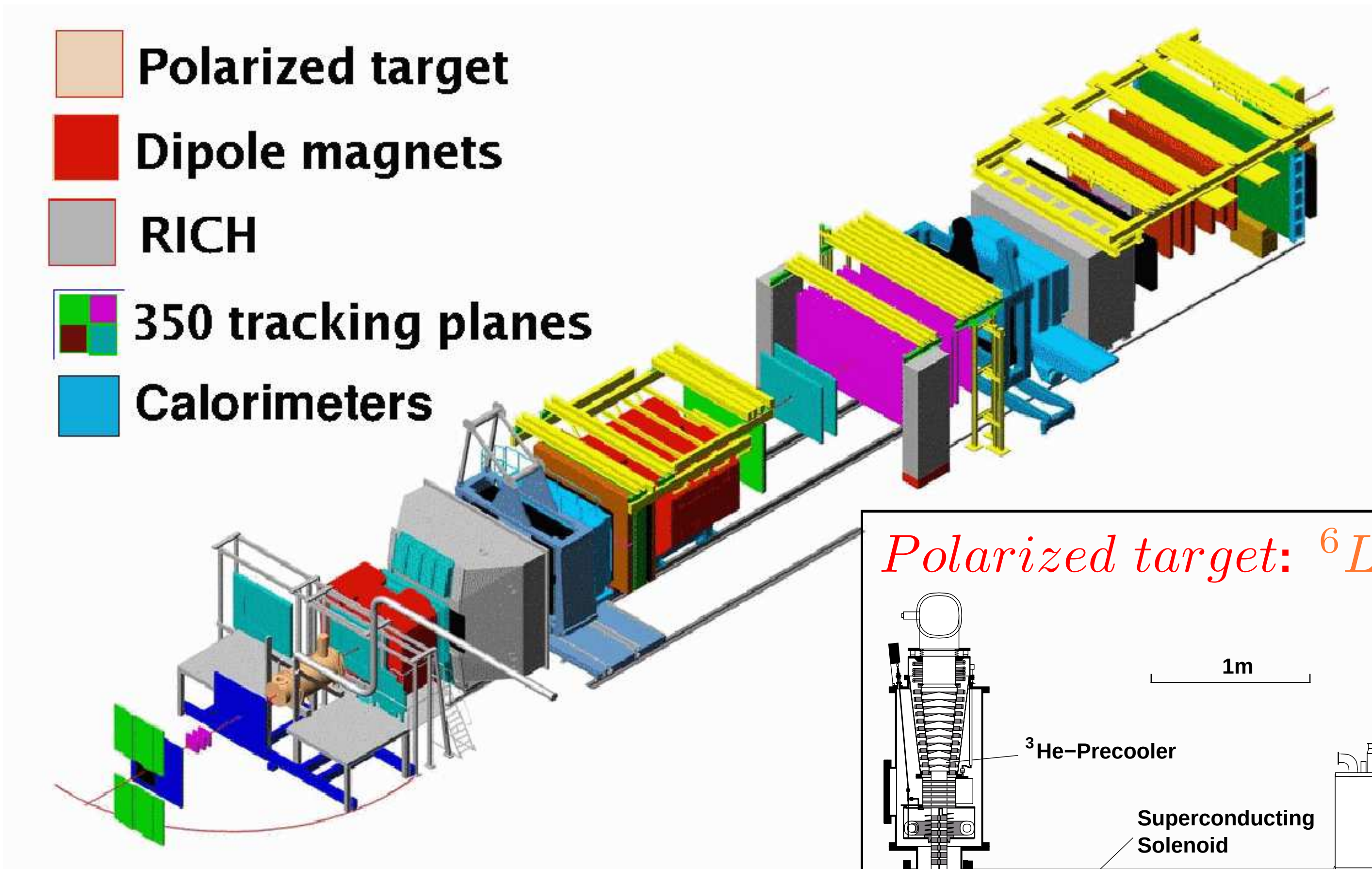
$$\boxed{f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)}$$

$$\boxed{h_{1}^{\perp}(DY) = -h_{1}^{\perp}(SIDIS)}$$

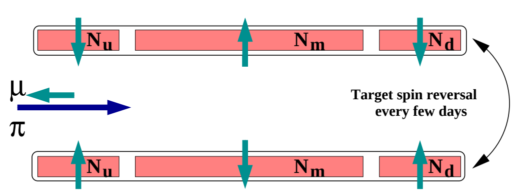
This sign change is considered a crucial test of non-perturbative QCD: the QCD TMD factorization and the TMD approach itself.

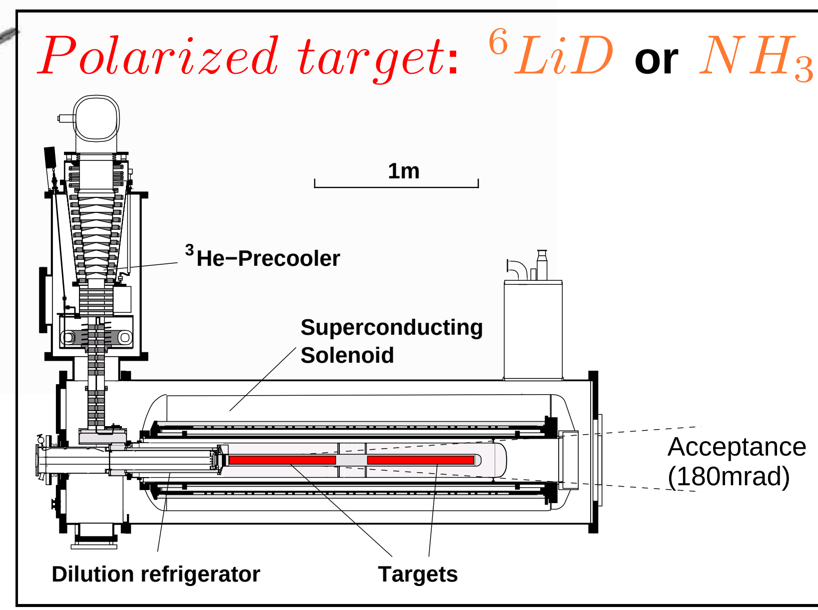
In COMPASS, we have the opportunity to test this sign change using the same spectrometer and transversely polarized target.

# The COMPASS Experiment at CERN




$\mu$ or $\pi$ beam



# Drell-Yan at COMPASS

- Availability of hadron beams (100 - 280 GeV/c):
  $\pi^-$ beam @190 GeV/c (4% kaons contamination, $<$1% $\bar{p}$).
- A longitudinal/transversely polarized target system:

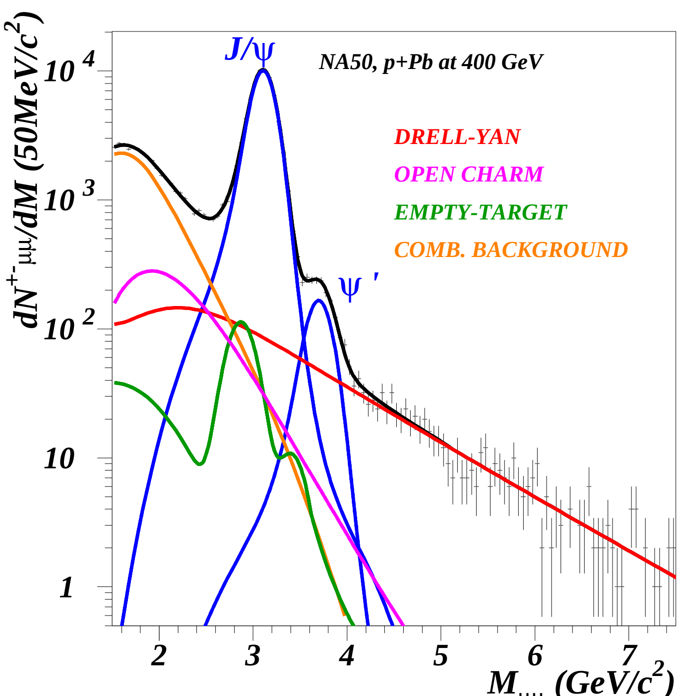
| material | $^6LiD$ | $NH_3$ |
|---|---|---|
| polarization | 50% | 90% |
| dilution factor | 0.4 | 0.22 |

- Long hadron absorber and beam plug downstream of the target.
- Muons angular acceptance: $30 < \theta < 140$ mrad.
- Dimuon trigger based on hodoscope signals coincidence, homothetic and pointing to the target.
- Long relaxation time of target polarization guaranteed by larger beam spot ($\sigma \approx$ 1cm) $\Rightarrow$ loose very small angle muons.

# High mass Drell-Yan

Detailed simulations using PYTHIA and GEANT. Results were compared with published cross-sections from past Drell-Yan experiments – good agreement.

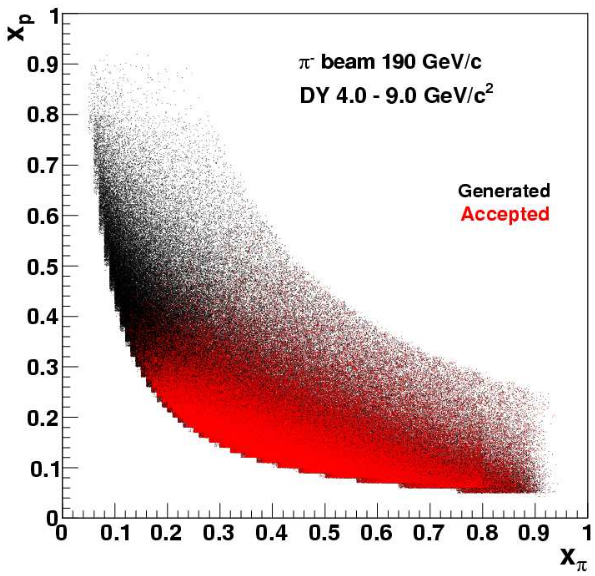
| $\sigma^{DY}_{\mu\mu}$ (nb) | $2 < M_{\mu\mu} < 2.5$ | $4 < M_{\mu\mu} < 9$ (GeV/c$^2$) |
|---|---|---|
| $\pi^-$p @190 GeV/c: PYTHIA (LO) | 0.63 | 0.14 |
| $\pi^-$p @190 GeV/c: PYTHIA*K-factor | 1.26 | 0.28 |




Even if the cross-section is low, dimuons with $4. \leq M_{\mu\mu} < 9.$ GeV/c$^2$ are the ideal sample to study azimuthal asymmetries in Drell-Yan, due to negligible background contamination.

# COMPASS acceptance

$\pi^-$ (190GeV/c) on $p^\uparrow$ interactions: $u$-quark dominance.




Valence quarks in the nucleon are probed.

In COMPASS, for DY $4 \leq M_{\mu\mu} \leq 9$ GeV/c$^2$, $x_p > 0.05$
$\hookrightarrow$ also the most favorable region to measure asymmetries, according to theory predictions.

Global acceptance for high mass dimuons: $\approx$ 35%

# Expected event rates

With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.2 \times 10^{32}\ cm^{-2} s^{-1}$ can be obtained
$\Longrightarrow$ expect 800/day DY events with $4 < M_{\mu\mu} < 9$ GeV/c$^2$.

Assuming 2 years of data-taking (140 days/year), one can collect:

- 230 000 events in DY HMR

This will translate into a statistical error in the asymmetries:

| Asymmetry | Dimuon mass (GeV/$c^2$) | | |
|---|---|---|---|
| | $2 < M_{\mu\mu} < 2.5$ | J/$\psi$ region | $4 < M_{\mu\mu} < 9$ |
| $\delta\, A_U^{\cos 2\phi}$ | 0.0020 | 0.0013 | 0.0045 |
| $\delta\, A_T^{\sin \phi_S}$ | 0.0062 | 0.0040 | 0.0142 |
| $\delta\, A_T^{\sin(2\phi+\phi_S)}$ | 0.0123 | 0.008 | 0.0285 |
| $\delta\, A_T^{\sin(2\phi-\phi_S)}$ | 0.0123 | 0.008 | 0.0285 |

$\hookrightarrow$ Possibility to study the asymmetries in several $x_F$ bins.

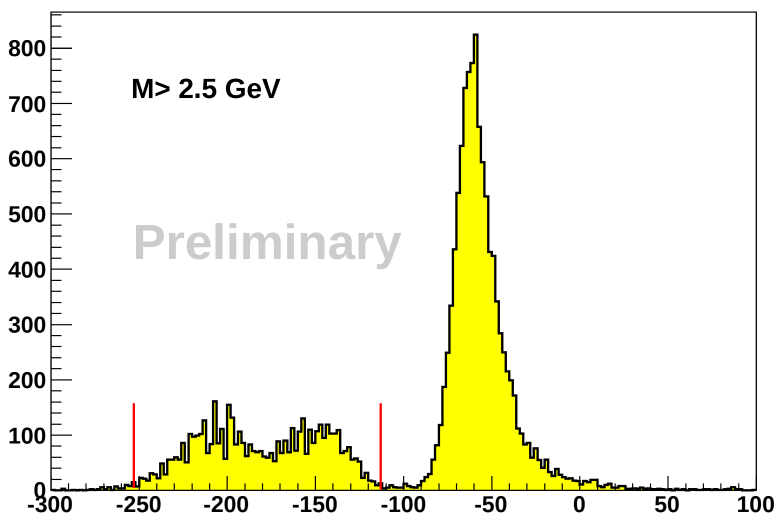
## *Feasibility studies*

Beam tests were done in 2007, 2008 and 2009 to study the feasibility of the measurement.

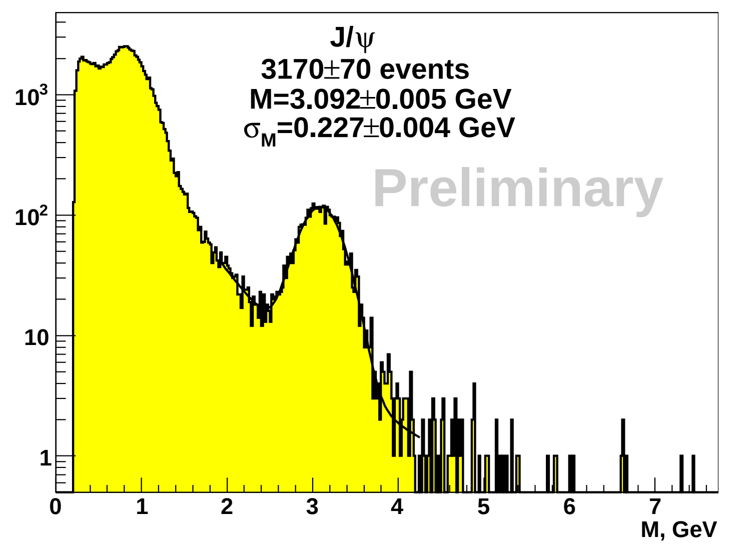
- The target temperature does not seem to increase significantly with the hadron beam, long polarization relaxation times measured (2007 beam test).
- Reasonable occupancies in the detectors closer to the target can only be achieved if a hadron absorber and beam plug is used (2008 beam test).
- Radiation conditions are within safety limits up to a beam intensity of $6 \times 10^7\ \pi^-$/second (measurements during all beam tests)
- Physics simulation were validated, within statistical errors (J/$\psi$ peak and combinatorial background, in 2007 and 2009 beam tests).

# Beam test 2009 results

$\pi^-$ beam 190 GeV/c on a plastic 2-cells target. A hadron absorber and a beam plug were used. The test lasted $\approx$ 3 days.




Reasonable $Z_{vertex}$ separation, allowing to distinguish the 2 target cells and the absorber.

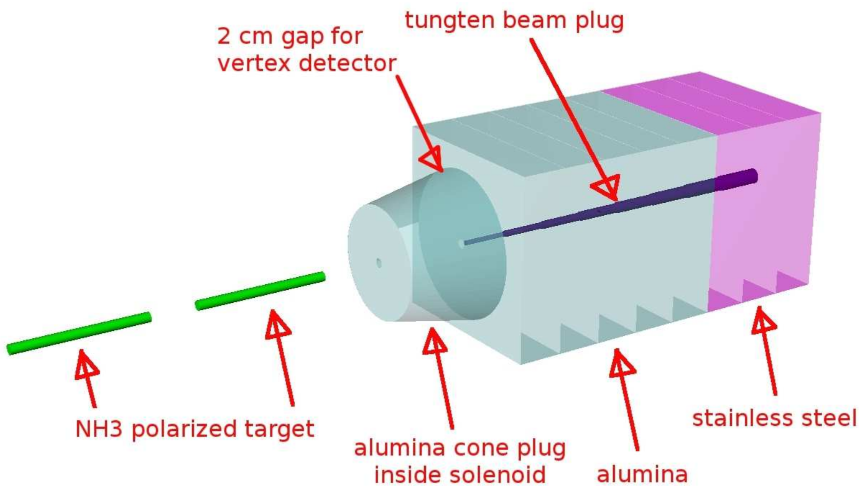


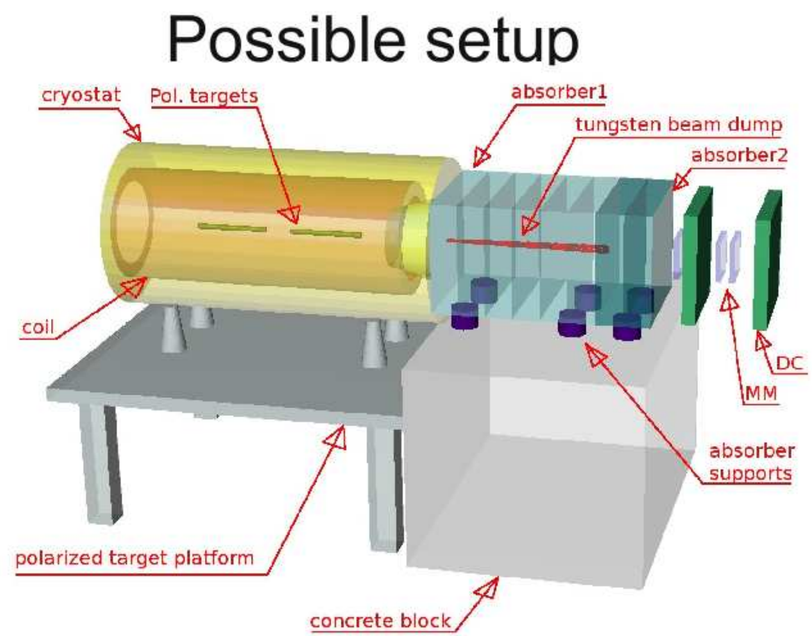

Mass resolution as expected, but worse than in previous experiments $\Rightarrow$ reconstruction program still needs optimization.

Combinatorial background (from uncorrelated $\pi$ decays) is estimated using the measured like-sign $\mu\mu$ distributions: the presence of the absorber reduces the background by a factor $\approx$ 10 at $M_{\mu\mu} = 2$ GeV/c$^2$.

# Optimization studies

Hadron absorber, beam plug and large area dimuon trigger are the main new components of the project. Optimization studies are ongoing.




- 2 target cells ($55 + 55$ cm), spaced by 20 cm, filled with $NH_3$, inside a 0.4T dipole.
- Absorber of $Al_2O_3$, 2.4 m long ($+$ steel), with beam plug (W) inside, 1.2 m long.
- 2 large area hodoscopes, for dimuon trigger in the $1^{st}$ spectrometer.
- Possibility to add a vertexing detector between target and absorber.

# Summary

- The polarized Drell-Yan measurement is part of the new COMPASS-II project.
- Proposal was approved by SPSC/CERN for a first period of 3 years (from 2012) including 1 year for Drell-Yan.
- Feasibility of the measurement was shown in the beam tests already performed.
- Sivers and Boer-Mulders PDFs sign change when measuring in Drell-Yan or in SIDIS will be checked.
- The expected statistical accuracy reached in 2 years will allow to check theory predictions and extract TMD PDFs, namely Sivers and Boer-Mulders, as well as the transversity PDF.

# SPARES: J/$\psi$-DY duality

J/$\psi$ and $\gamma$ being vector particles, the analogy between J/$\psi$ and DY production mechanisms might be of interest:

$$\pi^- p^\uparrow \to J/\psi X \to \mu^+\mu^- X \qquad\qquad \pi^- p^\uparrow \to \gamma^* X \to \mu^+\mu^- X$$

J/$\psi$ production via $q\bar{q}$ annihilation dominates at low-energies, justifying such analogy – J/$\psi$-DY duality.

From the study of J/$\psi$ production in the dileptons decay channel:

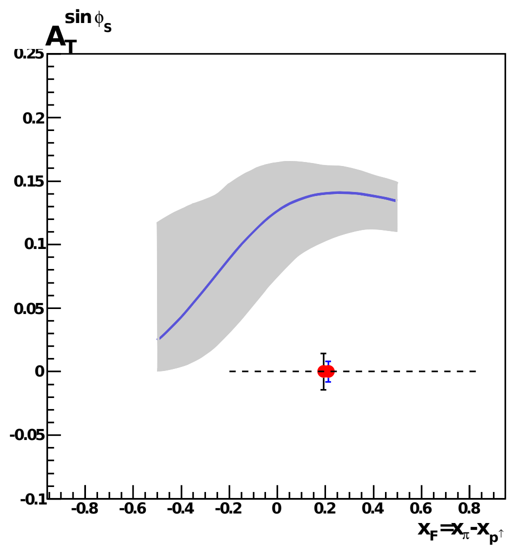
- Check duality hypothesis – polarized J/$\psi$ production cross-section
- Access PDFs from J/$\psi$ events – larger statistics available

Using secondary hadron beams it is possible to vary the beam energy (from 50 to 200 GeV), to study different J/$\psi$ production mechanisms.

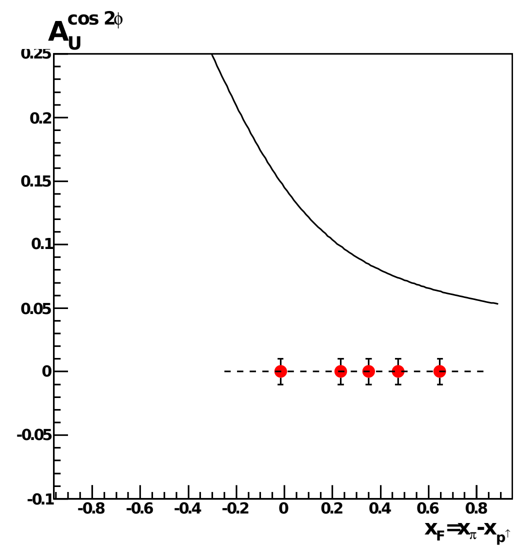
# SPARES: Comparing with theory predictions

DY $4. - 9.$ GeV/c$^2$

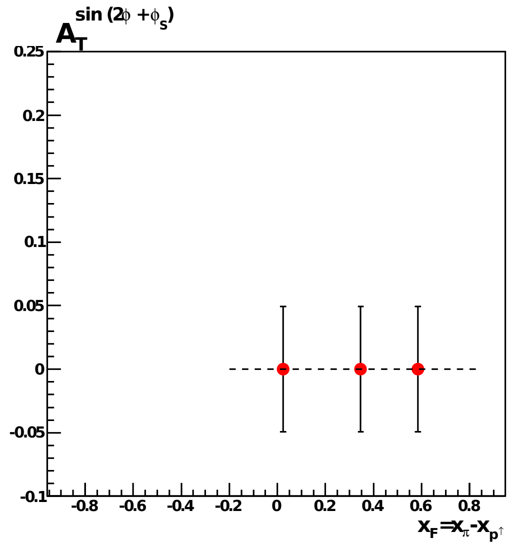
Sivers



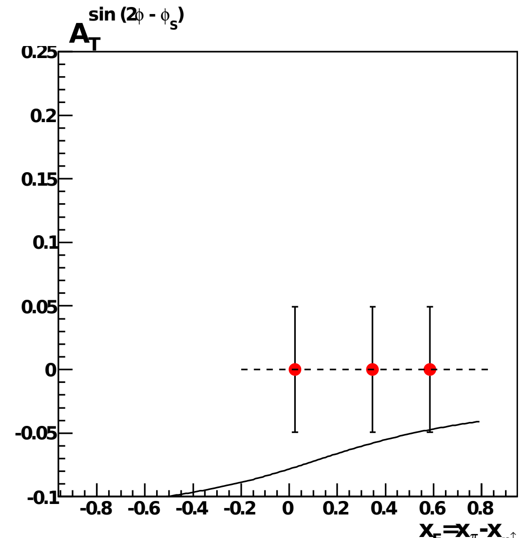

Boer-Mulders




BM $\otimes$ pretzelosity

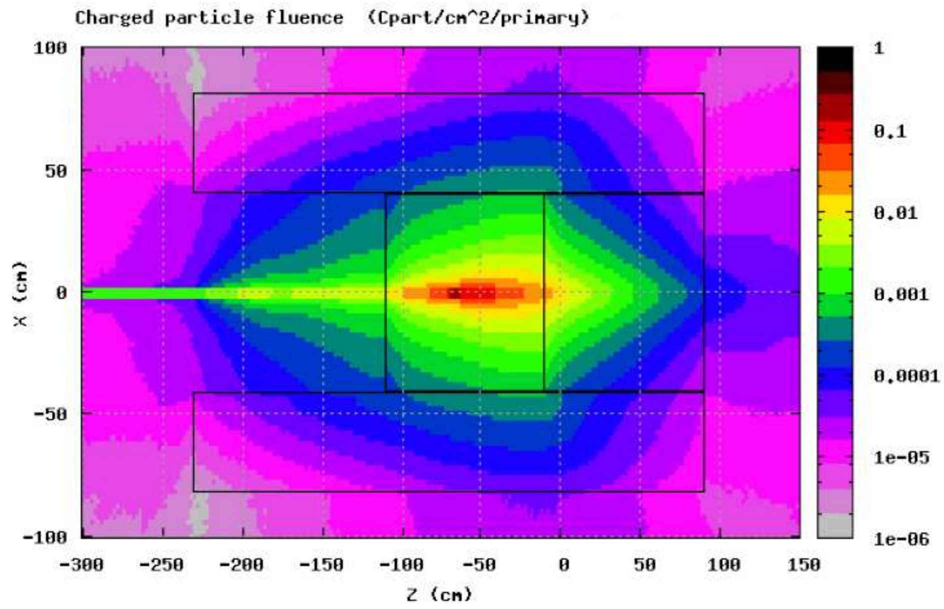



BM $\otimes$ transversity



# SPARES: Radiation conditions

COMPASS is a ground-level experiment, thus radiation conditions must be monitored, with appropriate shielding surrounding the target + absorber region:




FLUKA simulations describing the polarized target, absorber, beam plug and shielding, and the spectrometer, show that with beam intensity $6 \times 10^8$ to $1 \times 10^9$ $\pi^-$/spill the particles fluence is still below radio-protection limits, and safe for the detectors downstream.